GEO-SEQ Project
Quarterly Status and Cost Report
March 1 – May 31, 2002

Project Overview

The purpose of the GEO-SEQ Project is to establish a public-private R&D partnership that will:

- Lower the cost of geologic sequestration by: (1) developing innovative optimization methods for sequestration technologies with collateral economic benefits, such as enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coalbed methane production; and (2) understanding and optimizing trade-offs between CO_2 separation and capture costs, compression and transportation costs, and geologic sequestration alternatives.

- Lower the risk of geologic sequestration by: (1) providing the information needed to select sites for safe and effective sequestration, (2) increasing confidence in the effectiveness and safety of sequestration by identifying and demonstrating cost-effective monitoring technologies, and (3) improving performance-assessment methods to predict and verify that long-term sequestration practices are safe, effective, and do not introduce any unintended environmental impact.

- Decrease the time to implementation by: (1) pursuing early opportunities for pilot tests with our private-sector partners and (2) gaining public acceptance.

In May 2000, a project kickoff meeting was held at Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab) to plan the technical work to be carried out starting with FY00 funding allocation. Since then, work has been performed on four tasks: (A) development of sequestration co-optimization methods for EOR, depleted gas reservoirs, and brine formations; (B) evaluation and demonstration of monitoring technologies for verification, optimization, and safety; (C) enhancement and comparison of computer-simulation models for predicting, assessing, and optimizing geologic sequestration in brine, oil, and gas, and coalbed methane formations; and (D) improvement of the methodology and information available for capacity assessment of sequestration sites.

This Quarter's Highlights

- The first “time-lapse” casing measurement survey was completed at the Vacuum Field, New Mexico.
- Numerical simulations showed that CO_2 might be an effective cushion gas for a natural gas storage reservoir developed after CSEGR.
- Reactive-transport simulations were run, adding pyrite to the initial reservoir formation minerals and allowing oxygen fugacity in the injectate to vary. These changes have an impact on mineral stability, which in turn affect reservoir porosity.
- Stable carbon and oxygen isotopes in samples taken at the Lost Hills, California, field last February, show a larger contribution of “reservoir CO_2” than in samples collected in November 2001.
- The second workshop on “Numerical Modeling of Enhanced Coalbed Methane Recovery” was held in March.
- Researchers involved in the Frio Brine Pilot Project met in April to plan future field and laboratory activities.
- Initial processing results suggest that the changes in geophysical parameters induced by the Frio Brine Pilot Project CO_2 injection test might be too small to be monitored using surface seismic methods.

- Modeling studies of the Frio Brine Pilot injection experiments are improving our understanding of the interplay between injection volume, formation heterogeneity, fault boundaries and buoyancy flow.

Papers Presented, Submitted, Accepted, or Published during This Quarter

Benson, S.M. et al., 2002, The GEO-SEQ Project: A status report, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Doughty, C., S.M. Benson, and K. Pruess, 2002, Capacity investigation of brine-bearing sands for geologic sequestration of CO_2, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Hoversten, G.M., R. Gritto, T.M. Daley, E.L. Majer, and L.R. Myer, 2002, Crosswell seismic and electromagnetic monitoring of CO_2 sequestration, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Hovorka, S.D. and P.R. Knox, 2002, Frio Brine sequestration pilot in the Texas Gulf Coast, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Hovorka, S.D., C. Doughty, S.M. Benson, K. Pruess, and P.R. Knox, 2002, Assessment of the impact of geologic heterogeneity on CO_2 storage in saline aquifers: A case study from Houston, Texas, Paper Submitted to the Geological Society Special Publication “Geological Storage of Carbon Dioxide for Emissions Reduction,” S. Baines, J. Gale and R. H. Worden (editors).

Johnson, J.W. and J.J. Nitao, 2002, Reactive transport modeling of geologic CO_2 sequestration at Sleipner, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Johnson, J.W., Nitao, J.J., Newmark, R.L., Kirkendall, B.A., Nimz, G.J., Knauss, K.G. and Ziagos, J.P., 2002, Geologic CO_2 sequestration: Predicting and confirming performance in oil reservoirs and saline aquifers, AGU Annual Spring Meeting, Wash., D.C., May 28-31, 2002.

Law, D.H.-S, 2002. GEO-SEQ Project: Numerical model comparison study for greenhouse gas sequestration in coalbeds, Paper Presented at the COAL SEQ I Forum in Houston, Texas, U.S.A., March 14-15, 2002.

Law, D. H.-S., L.H.G. (Bert) van der Meer and W.D. (Bill) Gunter, 2002, Numerical simulation comparison study for enhanced coalbed-methane recovery processes, Part I: Pure carbon dioxide injection, SPE Paper No. 75669 Presented at SPE/CERI Gas Technology Symposium (GTS) 2002, Calgary, Alberta, Canada, April 30–May 2, 2002.

Law, D. H.-S., L.H.G. (Bert) van der Meer and W.D. (Bill) Gunter, 2002, Comparison of numerical simulators for greenhouse gas storage in coalbeds, Part II: Flue Gas Injection, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Law, D. H.-S., L.H.G. (Bert) van der Meer, P. Sammon and L. Pekot, 2002, New development on coalbed methane simulators for enhanced coalbed methane recovery processes, Paper Submitted to the 4th Annual CBM Conference, Calgary, Alberta, Canada, October 23-25, 2002.

Myer, L.R., G.M. Hoversten, and C.A. Doughty, 2002, Sensitivity and cost of monitoring geologic sequestration using geophysics, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Newmark, R., A. Ramirez, and W. Daily, 2002, Monitoring carbon dioxide sequestration using electrical resistance tomography (ERT): a minimally invasive method, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Oldenburg, C.M., D. H.-S. Law, Y. Le-Gallo, and S.P. White, 2002, Mixing of CO_2 and CH_4 in gas reservoirs: Code comparison studies, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Oldenburg, C.M., S. Stevens and S.M. Benson, 2002, Feasibility of carbon sequestration with enhanced gas recovery (CSEGR), Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002.

Pruess, K. et al., 2002, Code intercomparison builds confidence in numerical models for geologic disposal of CO_2, 2002, Paper Accepted for Presentation at the GHGT-6 Conference, Kyoto, Japan, October 1-4, 2002

Zhu, J., K. Jessen, A. R. Kovscek, and F.M. Orr, Jr., Analytical solutions for coal-bed methane displacement by gas injection, SPE Paper 75255, Proceedings of the SPE/DOE Thirteenth Symposium on Improved Oil Recovery, Tulsa, OK, April 13–17, 2002.

Task Summaries

Task A: Develop Sequestration Co-Optimization Methods

Subtask A-1: Co-optimization of Carbon Sequestration, EOR, and EGR from Oil Reservoirs

Goals

To assess the possibilities for co-optimization of CO_2 sequestration and EOR, and to develop techniques for selecting the optimum gas composition for injection. Results will lay the groundwork necessary for rapidly evaluating the performance of candidate sequestration sites as well as monitoring the performance of CO_2 EOR.

Previous Main Achievements

- Screening criteria for selection of oil reservoirs that would co-optimize EOR and maximize CO_2 storage in a reservoir have been generated.
- An engineering approach to increase CO_2 storage during EOR was developed.

Accomplishments This Quarter

- A synthetic, three-dimensional, reservoir model that is consistent with a real field has been generated.

Progress This Quarter

We developed a synthetic, 3-D model of an oil reservoir based upon an actual field. The model incorporates uncertainty in that various realizations constrained by measured data can be obtained. Significant effort was expended to generate a limited number of realizations that span a range of reservoir behavior. Work was begun on delineating the CO_2 storage capacity of oil recovery under various reservoir scenarios.

Work Next Quarter

Work continues on considering various reservoir development scenarios to understand better reservoir development techniques that maximize the simultaneous production of oil and storage of CO_2. We are examining (in order): gravity drainage by injection into the top structure of a reservoir, water-alternating-gas (WAG) drive mode, CO_2 injection early in production life versus late in reservoir life, CO_2 injection following water flooding, and stripping of CO_2 from a mixture of CO_2 and N_2 that simulates an incompletely separated combustion gas.

Subtask A-2: Feasibility Assessment of Carbon Sequestration with Enhanced Gas Recovery (CSEGR) in Depleted Gas Reservoirs

Goals

To assess the feasibility of injecting CO_2 into depleted natural gas reservoirs for sequestering carbon and enhancing methane (CH_4) recovery. Investigation will include assessments of (1) CO_2 and CH_4 flow and transport processes, (2) injection strategies that retard mixing, (3) novel approaches to inhibit mixing, and (4) identification of candidate sites for a pilot study.

Previous Main Achievements

- On the basis of numerical-simulation studies, the proof-of-concept of CO_2 storage with enhanced gas recovery (CSEGR) has been demonstrated.
- Initial feasibility was assessed through numerical simulation of CO_2 injection into a model system, based on the Rio Vista gas field in California.
- The numerical-simulation capability supporting this assessment is being improved through enhancement to the TOUGH2-EOS7C code.

Accomplishments This Quarter

- Simulations of gas storage in a depleted gas reservoir after CSEGR were carried out. The large effective compressibility of CO_2 around the critical pressure may make it an ideal cushion gas.
- A subcontract with Advanced Resources International was activated to perform economic-feasibility assessment studies for CSEGR.

Progress This Quarter

Curt Oldenburg carried out simulations of the use of CO_2 as a cushion gas in natural gas (CH_4) storage. Carbon dioxide may be an effective cushion gas because of its large effective compressibility around the critical pressure, as well as its large density relative to methane. Preliminary simulations suggest that 30% more CH_4 can be stored using CO_2 as a cushion gas as opposed to a native cushion gas (**Figure 1).** Similar to CSEGR, the extent of gas mixing is a critical issue for the use of CO_2 as a cushion gas.

Oldenburg also presented a talk entitled "CO_2 Injection for Carbon Sequestration with Enhanced Gas Recovery," on May 14 at Stanford's Petroleum Engineering Department.

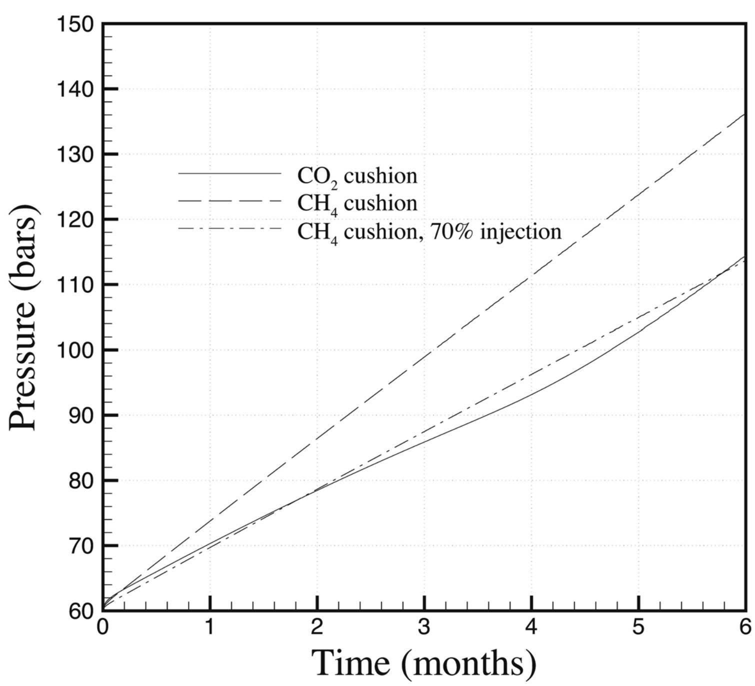

Figure 1. Pressure as a function of time in the model gas reservoir as CH_4 is injected for three cases: (1) native CH_4 gas cushion; (2) CO_2 gas cushion; and (3) native CH_4 gas cushion (injection rate is 70% that of the other cases)

We developed and activated the subcontract to Scott Stevens (ARI), and met with him in Berkeley to kick off the economic feasibility assessment work for CSEGR. Scott will be a co-author on the paper we will present on this subject at the Kyoto meeting in October 2002.

Work Next Quarter

This subtask group will write a draft paper on the use of CO_2 as a cushion gas for gas storage as an end-use of a depleted gas reservoir that has undergone CSEGR. The group will assist Scott Stevens (ARI) as needed in the economic-feasibility assessment work. In addition, the group will continue to search for a potential CSEGR pilot site with contacts developed at the February 2002 SPE meeting at Villahermosa. It will also continue investigations comparing DGM and ADM, including variation in Knudsen coefficient as a function of permeability.

Subtask A-3: Evaluation of the Impact of CO_2 Aqueous Fluid and Reservoir Rock Interactions on the Geologic Sequestration of CO_2, with Special Emphasis on Economic Implications.

Goals

To evaluate the impact on geologic sequestration of injecting an impure CO_2 waste stream into the storage formation. By reducing the costs of the front-end processes, the overall costs of sequestration could be dramatically lowered. One approach is to sequester non-pure CO_2 waste streams that are less expensive or require less energy than separating pure CO_2 from the flue gas.

Previous Main Achievements

- Potential reaction products have been determined; using reaction-progress chemical thermodynamic/ kinetic calculations, for typical sandstone and carbonate reservoirs into which an impure CO_2 waste stream is injected.

Accomplishments This Quarter

- Reactive-transport (open system) chemical kinetic simulations were run using the reactive transport simulator CRUNCH (Steefel, 2001).

- Confirmatory reactive-transport experiments were planned to lend credibility to the model calculations and simulations done to date and planned for the future.

- Assembly was completed of a redesigned Plug Flow Reactor (PFR), which will be used to conduct the reactive-transport experiments. Its temperature and pressure measurement devices and data-logging system were checked and calibrated.

Progress This Quarter

We continued the process of evaluating the impact of waste stream CO_2, as well as contaminants (e.g., SO_2, NO_2, and H_2S), on injectivity and sequestration performance. At the annual program review held in late January 2002, the GEO-SEQ Advisory Committee was presented the results of our preliminary reactive transport simulations. Their specific recommendations regarding this work were to: (1) conduct confirmatory reactive-transport experiments to lend credibility to the model calculations and simulations done to date and planned for the future, and (2) perform simulations that added pyrite to the mix of initial reservoir rock minerals and that allowed the O_2 fugacity to be relatively high in the injected CO_2-rich fluid and to vary (i.e., not to be fixed at the initial, unperturbed reservoir value). We addressed the second recommendation by running additional cases for all of the reactive transport simulations done to date, but this time using the modified conditions recommended by the Committee.

As an example of the results obtained in the new simulations, we now describe a simulation of the reaction of a NaCl-type brine equilibrated with an injected fluid phase consisting of 80 bar CO_2 and 10 bar H_2S in the presence of the base case carbonate reservoir rock at 60°C. In these new runs, we split the volume of Fe in the reservoir rock equally between siderite and pyrite at 0.5% each, rather than have it all represented as siderite only. All the other base case carbonate reservoir characteristics remained the same, with an initial porosity of 33% and the bulk of the rock split 50:50 between calcite and dolomite. The initial composition of the brine was that produced by equilibrating a seawater-ionic-strength-equivalent NaCl solution with the reservoir rock. In this new run, however, the O_2 fugacity was not fixed to an arbitrary, reasonable low value appropriate for the assumed mineral assemblage as the initial equilibrated value, but rather was allowed to float, dictated by any redox reactions that might occur. In a similar manner, we increased the O_2 fugacity in the injected fluid to a maximum value that could be maintained in equilibrium with the injected fluids and the initial minerals in the reservoir rock. We then followed chemical reactions through space and time along a 50 m length of reservoir rock for a 10-year time period as the CO_2-rich brine continuously flowed through it, displacing the original pore fluid. We used a linear flow rate of 4 m/y, which happens to be the natural (pre-injection) basinal flow rate for the Utsira Formation (Zweigel et al., 2001). This formation is the sandstone reservoir unit being used for CO_2 sequestration in the Sleipner field. The results during 10 years of reaction are presented in **Figure 2**, where they are compared with the comparable earlier runs (top three panels), in which no pyrite was present and in which O_2 fugacity was fixed.

In the two leftmost panels in **Figure 2** are plotted the pH and the concentration of the dominant sulfur-bearing aqueous species in the first cell of the reactive-transport simulation over the course of the 10-year run. Although the pH is nearly identical in both simulations, the S-species differ considerably (much more HS^- in the pyrite-present case); and although it is hard to discern on the log scale, the SO_4 concentration is also lower in the pyrite-present case. This has an impact on mineral stability, as seen in the middle pair of panels, where the presence of pyrite destabilizes the siderite (it converts to pyrite), and much less calcite is converted to anhydrite. This, in turn, impacts porosity, such that in the first cell a slight porosity loss (owing to the greater molal volume of anhydrite versus calcite) switches to porosity gain when pyrite is present.

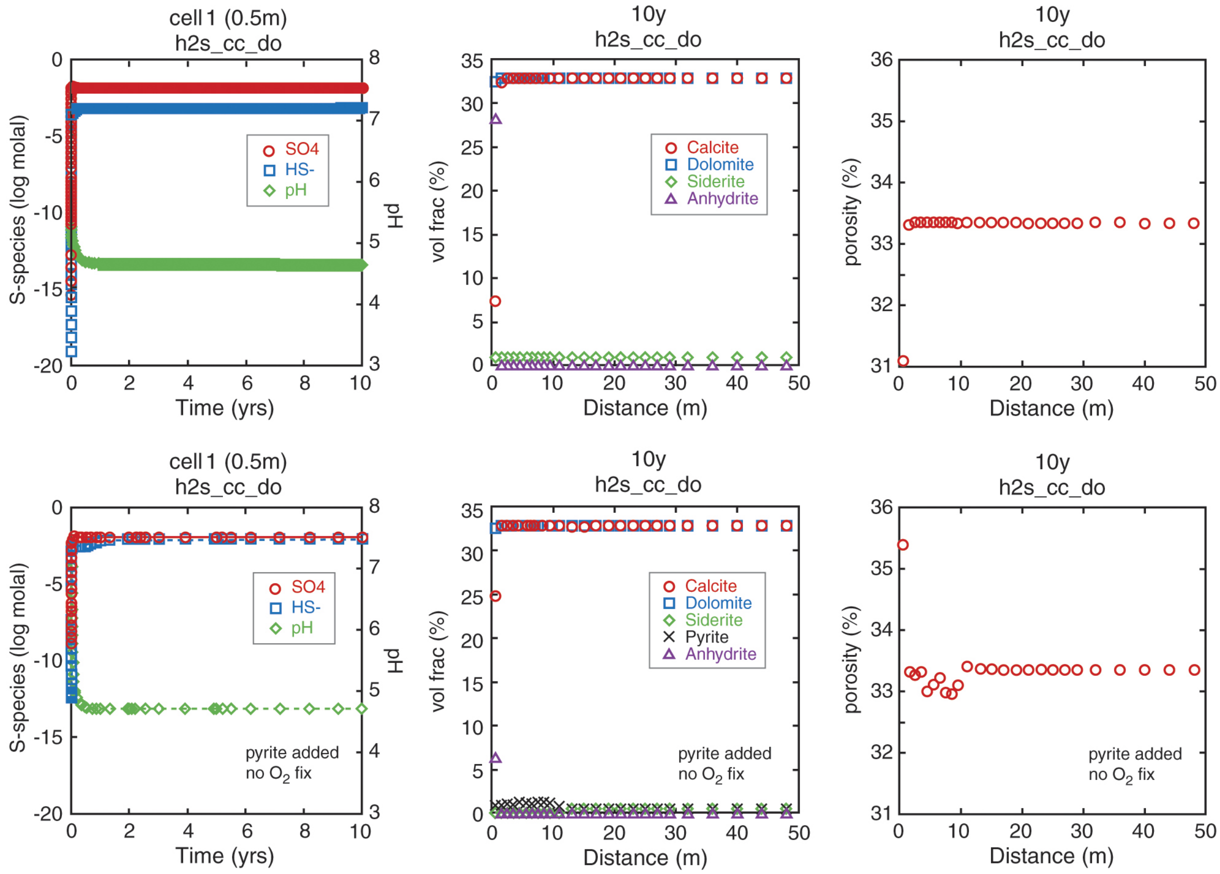

Figure 2. Simulation results for ten years of reactions (see text for details)

During this quarter, we also began making modifications to our Plug Flow Reactor (PFR) system, to allow us to conduct reactive-transport experiments analogous to the reactive transport simulations that we have been making. This was an item of high priority to the Advisory Committee. Our PFR system (**Figure 3**) is comprised of a high-temperature Ti-column plug flow reactor with Au core liners and associated furnace, controller, a Quizix computer-controlled high-pressure, two-piston metering pump, dome-type back pressure regulator, and other minor components. This reactor operates at temperatures up to 350ºC and pressures up to 300 bars. Flow rates from 0.0001 to 10 ml/min are achievable. A differential pressure transducer plumbed across the core allows monitoring of Darcy permeability “on the fly”. To begin with, we altered the plumbing to allow us to add a second Quizix pulseless, computer-controlled, high-pressure, two-piston pump. This permits fluid mixing upstream from the column. We then pressure tested all lines and completely recalibrated all pressure and temperature measuring devices, readouts and the 32-channel data logger into which all signals are fed. Our plan is to first use the PFR system to conduct experiments relevant to the Frio Brine Pilot Project (Task E).

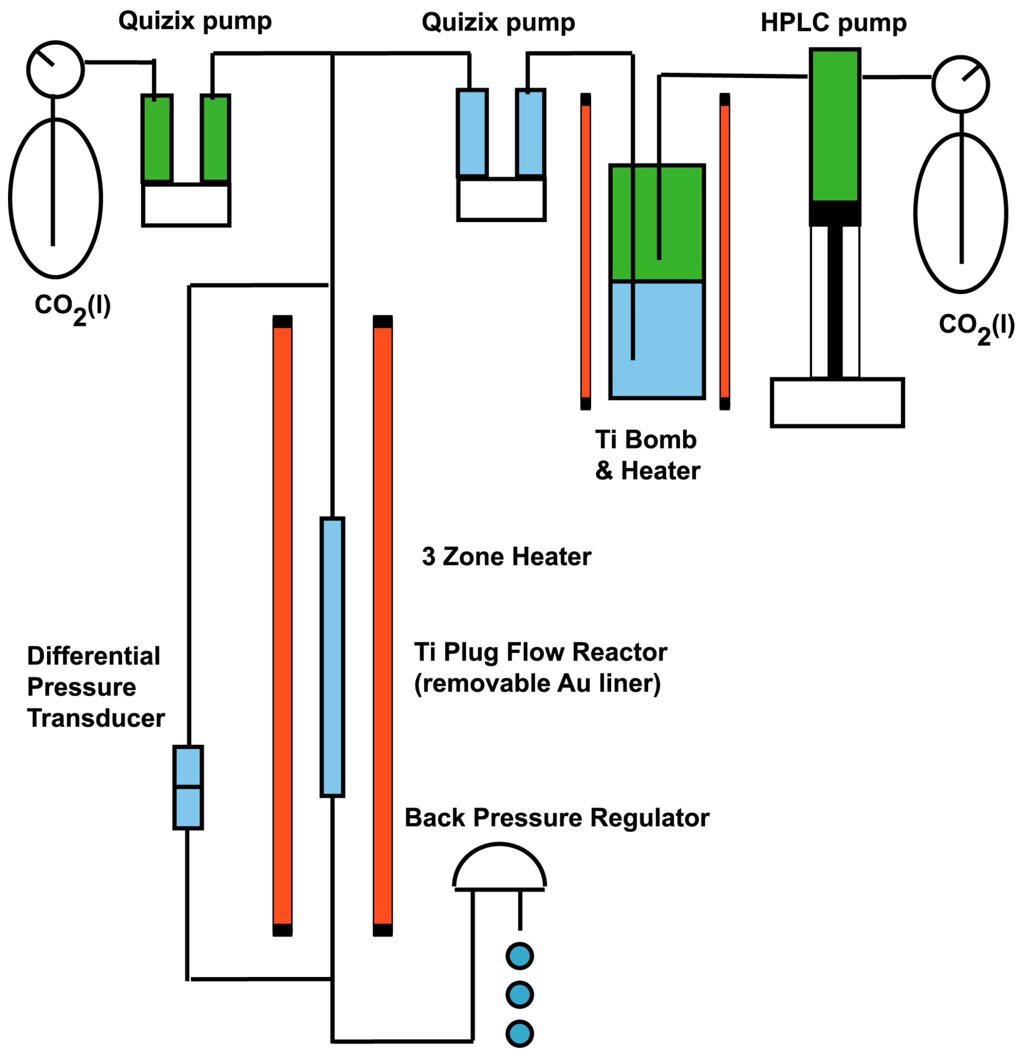

Figure 3. Simplified schematic of the Plug Flow Reactor system

The paper "Geologic CO_2 sequestration: Predicting and confirming performance in oil reservoirs and saline aquifers" was presented during the AGU Annual Spring Meeting (Washington, D.C., May 2002).

Work Next Quarter

We will continue investigating the impact of other contaminants (SO_2, H_2S, NO_2, etc.) in the CO_2 waste stream. Our attention will become more focused on doing work that may help in the design and conduct of the Frio Brine Pilot Project (Task E).

Task B: Evaluate and Demonstrate Monitoring Technologies

<u>Subtask B-1: Sensitivity Modeling and Optimization of Geophysical Monitoring Technologies</u>

Goals

To (1) demonstrate methodologies for, and carry out an assessment of, the effectiveness of candidate geophysical monitoring techniques; (2) provide and demonstrate a methodology for designing an optimum monitoring system; and (3) provide and demonstrate methodologies for interpreting geophysical and reservoir data to obtain high-resolution reservoir images. The Chevron CO_2 pilot at Lost Hills, California, is being used as an initial test case for developing these methodologies.

Previous Main Achievements

- A methodology for site-specific selection of monitoring technologies was established and demonstrated.

Accomplishments This Quarter

- Numerical results of flow simulations for the site of the Frio Brine Pilot Project, Texas, were converted into changes in geophysical parameters.

Progress This Quarter

Numerical modeling of the Frio Brine Pilot Project (Task E) CO_2 injection test was conducted. The initial flow simulation model of that field experiment was converted to geophysical parameters using limited well log data to construct petrophysical relations. Log data was extremely limited so that many assumptions were required. One finding from study of available log data was that the porosity of 0.3, which had been assumed for the target "B" sand, was not compatible with measured resistivities. Resistivity logs suggested that the porosity was significantly lower. This also implies that permeability may be quite smaller than assumed and may impact projected injection rates.

Because only Vp information was available from a single log, we have assumed a spherical grain model in conjunction with Gassman's equations and adjusted the bulk modulus and Poisson's ratio of the grains to match observed velocities in the B sand. No porosity or saturation logs have been provided; thus, a generic Archie's Law as been assumed to calculate electrical resistivities.

Results from three time steps from the flow simulation model, at 0, 50 and 100 days into CO_2 injection, have been converted to seismic velocity, density, and electrical resistivity.

Numerical modeling is continuing. To date, surface seismic, VSP and crosswell EM numerical data sets have been generated. Analysis is not complete, but initial processing suggests that the changes induced by CO_2 injection will be too small to be monitored using surface seismic methods.

Work Next Quarter

Numerical modeling to obtain geophysical data sets for synthetic CO_2 injection tests at the Frio Brine Pilot site, Texas, will continue. Computed EM and VSP data will be analyzed.

<u>Subtask B-2: Field Data Acquisition for CO_2 Monitoring Using Geophysical Methods</u>

Goals

To demonstrate (through field testing) the applicability of single-well, crosswell, surface-to-borehole seismic, crosswell electromagnetic (EM), and electrical-resistance tomography (ERT) methods for subsurface imaging of CO_2.

Previous Main Achievements

- The first test of the joint application of crosswell seismic and crosswell electromagnetic measurements for CO_2 monitoring was completed.

Accomplishments This Quarter

- A second set of casing surveys at ChevronTexaco's Vacuum Field was performed, constituting the first "time-lapse" measurements over a portion of the field where CO_2 injection is planned. Casing surveys were extended to include a region in which CO_2 is currently being injected.

- Casing surveys were obtained during normal field operations (during active pumping and injection), with no adverse results.

Progress This Quarter

Using results from the baseline survey combined with laboratory results, a second set of field casing surveys were successfully conducted at the Vacuum field in May. The initial survey was conducted using the same measurement protocol as was used in the original, baseline data set. For these measurements, the wells were disconnected from surface electrical and piping systems. Additional data were obtained using improved, symmetric measurement schedules, which are designed to produce more balanced measurements across the well pattern. These data sets will constitute a new baseline for future surveys to reference.

A key question to address in long-term monitoring with minimum impact to operations is the safety of personnel and equipment during active measurements, when the well casings are connected to surface piping and electrical systems. A series of measurements was designed to test the potentials generated when well casings are used as current electrodes during measurement. After the initial data were obtained, the wells were re-connected to the surface electrical and piping system. All the pumping and injection operations returned to normal usage. Within the well pattern, working hardware included submersible and rod and rocker pumps, as well as water injection. A series of measurements were made to ensure safe operations for both personnel and equipment as power was applied to individual well pairs. Touch potentials remained well within safe ranges, even when full power was applied. No adverse changes were detected on the equipment lines.

Measurement of key data sets was repeated, with all wells connected to surface piping and electrical systems. Data quality "connected" versus "disconnected" was compared to determine the signal degradation caused by pumping and electrical effects. Field analysis indicated signal-to-noise degradation to be within tolerable limits. Analysis of these results continues.

Injection of CO_2, which had been planned for the main well pattern, had been postponed in the central wells of the original pattern over which the surveys had been conducted. During the intervening seven months, these wells had been used for a water flood. Analysis of the processed data will focus on the detection of changes consistent with water flood operations.

Carbon dioxide is being injected into the wells immediately adjacent to the original well pattern. We extended the range of the casing survey and collected additional data, including two wells used for the CO_2 flood. These measurements were obtained with all wells connected and operating under normal conditions. Analysis of the processed data will focus on detection of changes consistent with CO_2 migration.

Work Next Quarter

Field data will be processed and interpreted. A subsequent set of measurements to assess movement of CO_2 in the reservoir is planned for the late summer. Initial models will be run to assess the sensitivity of the ERT method to detect changes resulting from the proposed injection of CO_2 into the Frio formation as part of the Frio Brine Pilot Project (Task E).

Subtask B-3: Application of Natural and Introduced Tracers for Optimizing Value-Added Sequestration Technologies

Goals

To provide methods that utilize the power of natural and introduced tracers to decipher the fate and transport of CO_2 injected into the subsurface. The resulting data will be used to calibrate and validate predictive models utilized for (1) estimating CO_2 residence time, reservoir storage capacity, and storage mechanisms; (2) testing injection scenarios for process optimization; and (3) assessing the potential leakage of CO_2 from the reservoir.

Previous Main Achievements

- Laboratory isotopic-partitioning experiments and mass-balance isotopic-reaction calculations have been done to assess carbon- and oxygen-isotope changes (focused on the influence of sorption) as CO_2 reacts with potential reservoir phases.

Accomplishments This Quarter

- Noble gas isotope (e.g., Ar vs. Xe) measurements of gases, obtained in November 2001 during the second sampling episode, exhibited two possible mixing trends that diverge from an injectate CO_2 signal.

- Stable carbon and oxygen isotope data obtained from a third sample set of six wells taken at Lost Hills in February 2002 indicated a much smaller contribution of injection CO_2 than that shown by the November 2001 samples.

Progress This Quarter

Noble Gas Isotopes

B. Mack Kennedy and Matthijs van Soest of Berkeley Lab's Center for Isotope Geochemistry initiated a preliminary study on the potential of noble gas isotope geochemistry for characterizing indigenous reservoir fluids and the flow paths and infiltration rate of CO_2 injected in the Lost Hills system. This work also seeks to merge noble gases with other isotope and geochemical techniques, geophysical imaging, and structural constraints.

The field-scale test of CO_2 injection into the Lost Hills, San Joaquin Basin, California, oil and gas field consisted of three parallel projects: seismic and electrical imaging, co-injection of chemical and isotopic tracers, and chemical and isotopic analyses of production fluids before and after CO_2 injection. Samples were analyzed for noble gas abundance and isotopic compositions collected from observation wells, laid out in a rectangular grid surrounding several CO_2 injection wells, and from the source of the injected CO_2. Samples were collected prior to injection from wells 11-8D, 12-8D and 12-7, at the end of the first major CO_2 injection period (12/6/00; 1/4/01) and during a period when water was being injected into the system (11/20/01, with three additional wells: 11-7B, 11-9J and 12-8C).

Unfortunately, the pre-injection and first post-injection test samples were contaminated with atmospheric gas introduced, presumably, during sampling. The contamination inhibited their utility as a measure of the indigenous noble gas composition of the gas field. The second set of post-injection samples was not air contaminated. Combined with an analysis of the injected CO_2, their compositions (e.g., **Figure 4**) demonstrate that, (1) noble gases are potentially very sensitive tracers for the return of the injected CO_2, (2) they can be used to calculate the fraction of injected CO_2 collected at the observation wells, and (3) that each observation well experienced variable returns of the injected CO_2. The latter is consistent with observed changes in bulk gas chemistry and carbon isotopic compositions. Unfortunately, however, because of the present understanding of the indigenous reservoir composition, it is difficult to calculate the amount of return. A third set of samples, which were taken on February 14, 2002, prior to a new CO_2 injection test (May 2002), may help improve our understanding of the indigenous reservoir composition, if the reservoir had recovered sufficiently from the previous injection test.

Changes in bulk gas chemistry, and the carbon and oxygen isotopic composition of the CO_2 produced before and after injection, indicated a significant amount of gas mixing, gas-gas, and perhaps gas-rock isotopic exchange. However, the bulk gas chemistry and carbon isotopic data alone cannot provide a quantitative measure of the proportion of CO_2 collected at the observation wells that was injected into or was indigenous to the reservoir. This information is necessary to model the extent and path of isotopic exchange indicated by the changes in bulk gas chemistry and isotopic composition. However, because of their inert chemical characteristics, the noble gases could have unambiguously provided this information if the background set of samples had not been contaminated.

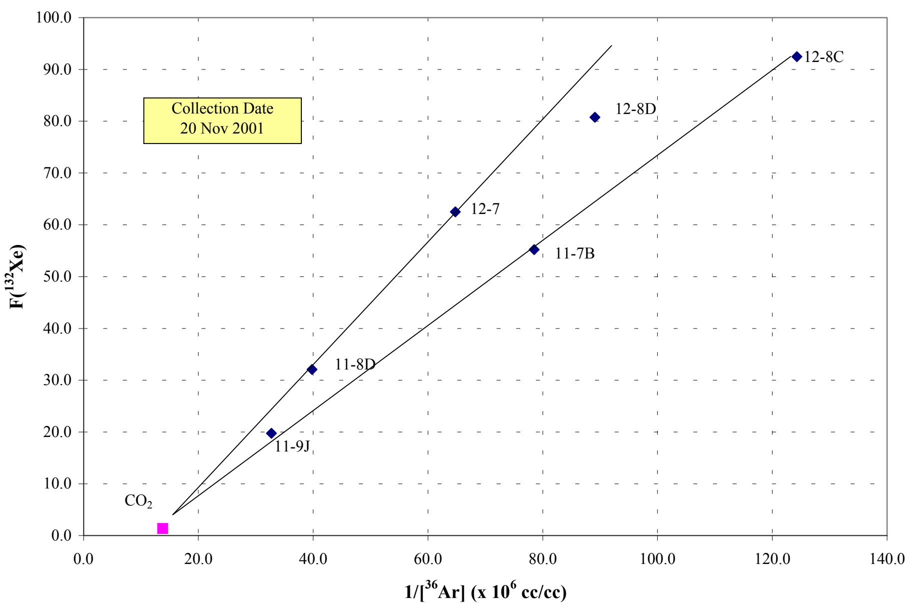

Figure 4. A plot showing F (Xe) values (the Xe/Ar ratio normalized to the atmospheric ratio) as a function of the inverse partial pressure of Ar for the second set of samples collected after the injection test. The datum labeled CO_2 is the composition of the injected carbon dioxide. We believe that the high (>>1) F (Xe) ratios are indigenous to the reservoir, as similar compositions have been observed at Elk Hills and other oil and gas fields (Hiyagon and Kennedy, 1992; Torgersen and Kennedy, 1999). The compositional trends suggest mixing between the indigenous reservoir fluids and the injected CO_2. If we had a better understanding of pre-injection compositions, the mixing lines in this figure could be used to calculate the proportion of recovered injected CO_2. Note the large difference between the Ar partial pressure and composition of the injected CO_2 and the fluid produced at the observation wells. [Hiyagon H. and Kennedy B. M. (1992), Noble gases in CH_4-rich gas fields, Alberta, Canada. Geochim. Cosmochim. Acta. 56, pp. 1569-1589. Torgersen, T. and Kennedy, B.M. (1999), Air-Xe enrichments in Elk Hills oil field gases: Role of water in migration and storage. Earth Planet. Sci. Lett., 167, pp. 239-253].

Stable Isotopes

Stable isotope compositions of carbon and oxygen have been determined on gases sampled from return wells in the Lost Hills system—11-8D, 12-7, 12-8D, 11-7B, 11-9J, and 12-8C. These samples were obtained on February 14, 2002 during an extensive period of water injection that started in mid-November 2001. Isotope compositions were also obtained on the CO_2 injectate that had been used prior to this water injection period. Its carbon ($\delta^{13}C$ = -31.9 ‰ vs. PDB) and oxygen ($\delta^{18}O$ = 1.9‰ vs.

SMOW) isotope values are very close to those determined from CO_2 injectate used at the very beginning of the Lost Hills injection project (Aug. 2000: -30.1 ‰ in $\delta^{13}C$ and –1.1 ‰ in $\delta^{18}O$).

These new carbon-oxygen isotope results are plotted in **Figure 5** together with results we had obtained from earlier samplings. The reservoir CO_2 has a very heavy carbon isotope signal compared to the injectate, providing a potentially sensitive tool to help distinguish the relative contributions of both. Although the sampling effort has not been particularly fine scale (i.e., closely spaced), we do observe a pronounced trend of isotopic enrichment in carbon with time, and to a lesser degree, enrichment in oxygen. Preliminary gas chemical analysis (work in progress) reveals that these most recently sampled wells are more enriched in CH_4 than those sampled in November 2001, suggesting that there is more of a "reservoir" contribution to these gases. Note also that compared to gases sampled during a CO_2 injection period, CO_2 obtained during periods when water was being injected is somewhat enriched in oxygen isotope compositions. An increased contribution by "reservoir CO_2" might play a major role in this. However, we cannot rule out the influence that a shift in the isotopic composition of the injected water could have, since the CO_2 will be enriched relative to water by some 30 to 40 ‰, depending on the temperature of the CO_2-H_2O oxygen isotope partitioning.

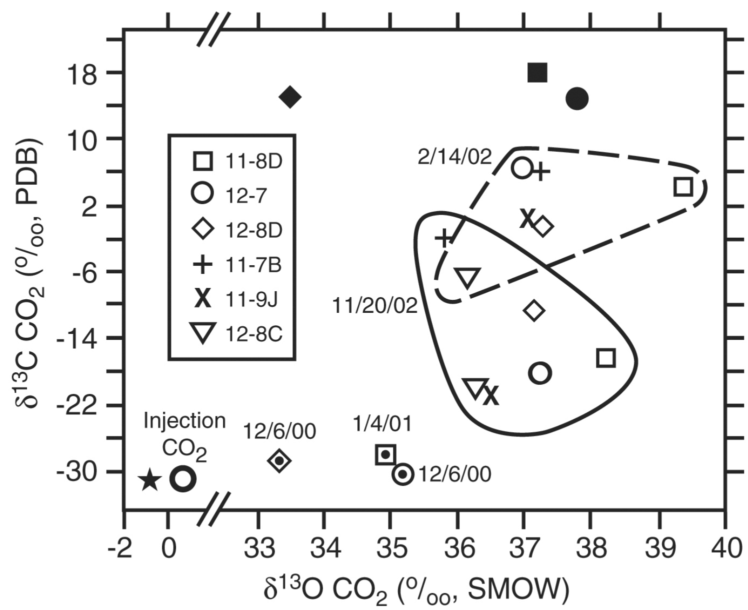

Figure 5. Plot of carbon versus oxygen isotope values determined from reservoir CO_2 (solid symbols, sampled in August of 2000 prior to CO_2 injection), CO_2 injectates (star: collected prior to CO_2 injection 8/11/00; half-filled circle: obtained on 2/14/02), and various wells from the Lost Hills, CA system. Sampling dates are indicated next to their respective values. Note that samples taken during December 2000 and January 2001 were obtained while CO_2 was being injected into the reservoir. The remaining samples (shown enclosed within solid or dashed regions) were collected during periods of water injection. A pronounced enrichment in carbon isotope values with time can be seen.

Introduced Tracers

Work this quarter was directed toward completing construction of the flow-through column apparatus and design of the initial laboratory tracer experiments. Discussions were initiated with Berkeley Lab modelers regarding incorporation of the tracers into TOUGH2 simulations for the Frio Brine Pilot Project injection test (Task E). Estimation of the physical properties necessary for incorporation into the model in advance of the laboratory testing is being completed. In addition, information necessary to satisfy regulatory requirements for the injection permitting is being pulled together in preparation for the early July meeting in Austin, TX.

Work Next Quarter

Efforts will focus on six main areas:

1. Continue chemical and isotopic assessment of the gases sampled on 2/14/01 at Lost Hills, CA. Obtain samples during the next CO2 injection test (June 2002).
2. Complete CO2 sorption-desorption experiments using Argonne Premium coals as well as Lost Hills core and mineral end-members, quartz, and calcite, and the Ottawa sand to high CO2 pressures (1 bar<P<250 bar).
3. Continue a modeling effort using Geochemist's Workbench to assess the magnitude of carbon and oxygen isotope partitioning during gas-brine-mineral reactions relevant to subsurface aquifer formation conditions.
4. Complete assembly of flow-through column apparatus and initiate laboratory testing of the applied tracers, using a coarse size fraction (20-30 mesh) of Ottawa sand.
5. Initiate preliminary modeling (with Berkeley Lab) of potential tracer behavior relevant for the Frio Brine Pilot Project injection test.
6. Design field-scale tracer injections for the Frio test.

Task C: Enhance and Compare Simulation Models

Subtask C-1: Enhancement of Numerical Simulators for Greenhouse Gas Sequestration in Deep, Unmineable Coal Seams

Goals

To improve simulation models for capacity and performance assessment of CO_2 sequestration in deep, unmineable coal seams.

Previous Main Achievements

- Reservoir simulator-code-comparison studies are providing a mechanism for establishing current capabilities, needs for improvement, and confidence in simulation models.

- Results from comparing the first two sets of simple numerical-simulation problems in Part I with pure CO_2 injection have been completed and published.

- Field data obtained from a single well, micro-pilot test with pure CO_2 injection conducted by the Alberta Research Council (ARC) at the Fenn Big Valley site, Alberta, Canada, have been released to participants for history matching (i.e., Problem Set 5). These data provide an opportunity to validate the new development in simulation models.

Achievements This Quarter

➢ GEO-SEQ Project, 2nd Workshop on “Numerical Modeling of Enhanced Coalbed Methane (ECBM) Recovery” was held to discuss how to represent the ECBM mechanisms correctly numerically, and how to proceed forward.

➢ Comparison for the Problem Sets 1 and 2 in Part II with flue gas injection is ongoing. Preliminary results from CMG’s GEM and BP’s GCOMP have been documented.

Progress This Quarter

GEO-SEQ Project, 2nd Workshop on “Numerical Modeling of Enhanced Coalbed Methane (ECBM) Recovery”, was held by ARC in Houston, Texas, on March 13, 2002. There were 20 participants: Rick Chalaturnyk (U. of Alberta, Canada), Steve Talman (U. of Alberta, Canada). Marc Bustin (U. of British Columbia, Canada), Sevket Durucan (Imperial College, U.K.), Ji Quan Shi (Imperial College, U.K.), George Moridis (Berkeley Lab, U.S.A.), Bill Gunter (ARC, Canada), David Law (ARC, Canada), Scott Reeves (ARI, U.S.A.), Larry Pekot (ARI, U.S.A.), Jeff Levine (CDX, U.S.A.), Peter Sammon (CMG, Canada), Jim Erdle (CMG, U.S.A.), Xavior Choi (CSIRO, Australia), Jim Flynn (GeoQuest, U.S.A.), Charlie Mones (WRI, U.S.A.), John Seidle (Sprouse, U.S.A.), Keith Greaves (TerraTek, U.S.A.), Matt Mavor (Tesseract, U.S.A.) and Bert van deer Meer (TNO, The Netherlands).

The main purpose of the workshop was to discuss the model comparison results to date, the future more complex problem sets, ECBM mechanisms that are and are not in the existing numerical models and their importance, how to represent these mechanisms correctly numerically, and the path forward. Details of this workshop can be found on the ARC’s password protected website: http://www.arc.ab.ca/extranet/ecbm/ (user name and password can be obtained by contacting David Law, law@arc.ab.ca) that includes the presentations given by Larry Pekot, Peter Sammon, and Bert van der Meer describing the new development on the CBM simulation models: ARI’s COMET2, CMG’s GEM and CSIRO/TNO’s SIMEDII, respectively.

Testing of Problem Sets 1 and 2, Part II with flue gas injection, is ongoing: (1) Problem Set 1 is a single-well flue gas injection/production test; (2) Problem Set 2 is a five-spot flue gas injection/production process. The numerical models being tested are CMG’s GEM, BP’s GCOMP, CSIRO/TNO’s SIMEDII and ARI’s COMET3. Preliminary comparison results between GEM and GCOMP are shown in **Figures 6 and 7.**

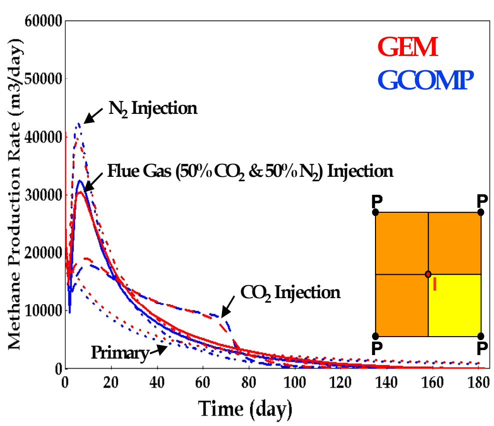

Figure 6. Problem Set 2:
Methane Production Rate

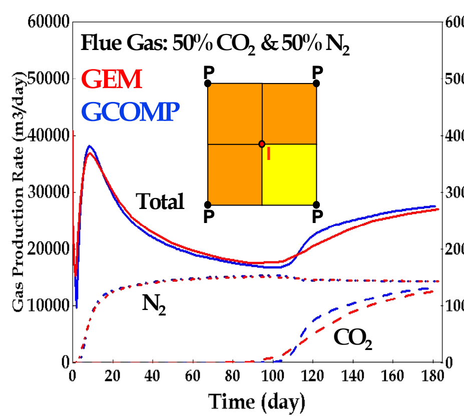

Figure 7: Problem Set 2:
Total Gas, CO_2 and N_2 Production Rates

The more complex Problem Sets 3 and 4, Part I with pure CO_2 injection, have been posted on the ARC’s website. These sets enhance Problem Set 2 by taking into account the effect of gas desorption time (or gas diffusion) between the coal matrix and the natural fracture system (Problem Set 3), and the effect of natural fracture permeability as a function of natural fracture pressure (Problem Set 4).

Model comparison study is ongoing with CMG's GEM, BP's GCOMP, CSIRO/TNO's SIMEDII and ARI's COMET2.
A confidential agreement has been signed by CMG to gain access to field data obtained from a single-well, micro-pilot test with pure CO_2 injection. The test conducted by the Alberta Research Council (ARC) at the Fenn-Big Valley site, Alberta, Canada, will provide history matching data to use with model GEM.

Work Next Quarter

David Law will complete the paper "Comparison of Numerical Simulators for Greenhouse Gas Storage in Coalbeds, Part II: Flue Gas Injection", and submit it to the 6th International Conference on Greenhouse Gas Control Technologies (GHGT-6).

ARC will collect and document the numerical results for Problem Sets 3 and 4 in Part I, with pure CO_2 injection, and for Problem Sets 1 and 2 in Part II, with flue gas injection.

<u>Subtask C-2: Intercomparison of Reservoir Simulation Models for Oil, Gas, and Brine Formulations</u>

Goals

To stimulate the development of models for predicting, optimizing, and verifying CO_2 sequestration in oil, gas, and brine formations. The approach involves: (1) developing a set of benchmark problems; (2) soliciting and obtaining solutions for these problems; (3) holding workshops of industrial, academic, and laboratory researchers; and (4) publishing results.

Previous Main Achievements

- A first workshop on the code intercomparison project was held at Berkeley Lab on October 29-30, 2001, with the first modeling results by different groups showing reasonable agreement for most problems.

Accomplishments This Quarter

- Further simulations were performed for the intercomparison test problems.
- Additional results were obtained from participating groups.
- First comparisons of results were made, and individual groups were contacted in an effort to reconcile differences.

Progress This Quarter

We performed further simulations for the intercomparison test problems and received additional results from participating groups. Results from different groups were compared, agreements as well as some discrepancies were noted, and several groups were contacted in an effort to reconcile differences. As an example, **Figures 8 and 9** show CO_2 fluxes from three groups for Test Problem 4, CO_2 discharge along a fault zone. The agreement between the different results was reasonable. We began drafting descriptions and discussions of simulation results.

Work Next Quarter

We will collect material from the various problem coordinators to document intercomparison of simulation results. An effort will be made to identify and reconcile differences between simulation results from different groups. A manuscript for the GHGT-6 conference will be written and submitted.

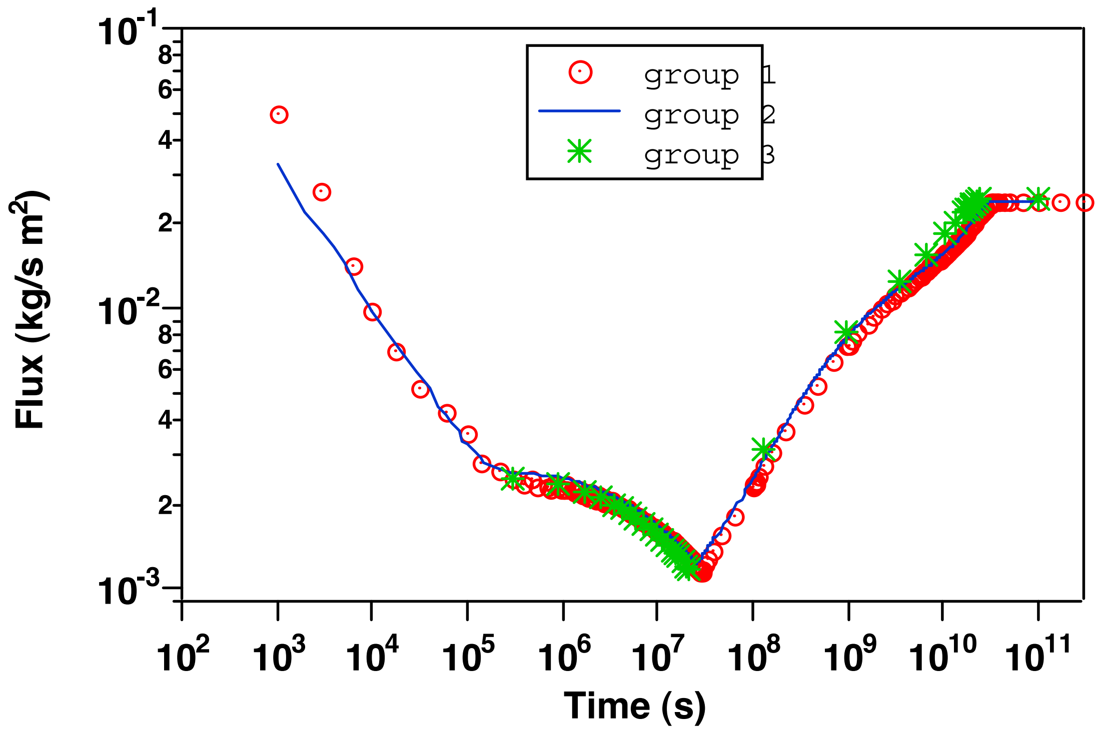

Figure 8. CO_2 flux entering at the bottom of the fault zone as a function of time

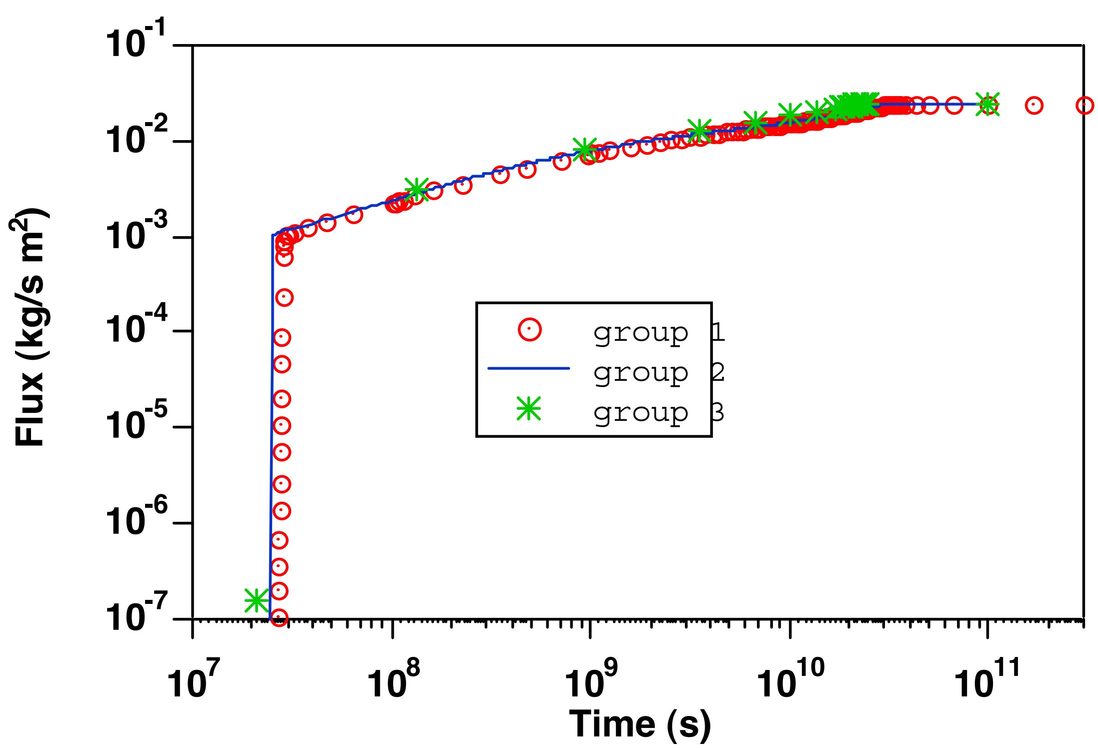

Figure 9. CO_2 flux exiting at the top of the fault zone as a function of time

Task D: Improve the Methodology and Information for Capacity Assessment

Goals

To improve the methodology and information available for assessing the capacity of oil, gas, brine, and unmineable coal formations; and to provide realistic and quantitative data for construction of computer simulations that will provide more reliable sequestration-capacity estimates.

Previous Main Achievements

- A new definition of formation capacity, incorporating intrinsic rock capacity, geometric capacity, formation heterogeneity, and rock porosity, was developed for use in assessing sequestration capacity.
- An assessment of California's CO_2 sequestration capacity was carried out.
- Factors affecting sequestration capacity of the Frio formation in Texas have been evaluated.
- The Texas Gulf Coast was targeted as an area from which a realistic data set could be generated for use in simulating brine-formation capacity.
- Location and identifying information were compiled for large industrial CO_2 emitters, and geologic data for the Frio and Oakville reservoirs were compiled.
- A realistic scenario for CO_2 injection into a brine formation was then designed for a site near Baytown, Texas; its brine-formation capacity for CO_2 storage was assessed based on numerical-simulation studies.

Accomplishments This Quarter

- Studies of the Frio Brine Pilot Project CO_2 injection experiment were conducted, using a heterogeneous model of the site
- An understanding of the interplay among CO_2 injection volume, buoyancy flow, formation heterogeneity, and sealed-fault boundaries was achieved.
- A new conceptual model and experimental protocol was developed for assessing sequestration effectiveness, a complement to sequestration capacity.

Progress This Quarter

New modeling studies of the Frio Brine Pilot Project CO_2 injection experiment (Task E) were conducted. Previous pilot-site modeling studies are described in the June-August 2001 report.

A set of figures showing the model and the results of four simulations (or "cases") are presented below. In the first two, 5,000 metric tonnes of CO_2 were injected at a constant mass rate over a period of 100 days. This was the amount of CO_2 originally envisioned for the pilot experiment and is the same as in previous pilot-site simulations. In the third and fourth cases, CO_2 was injected at a rate of 150 tonnes per day for one year, to more closely represent the conditions of a hypothetical full-scale CO_2 sequestration operation at the pilot project site. The higher injection rate is considered realistic for the Frio Brine Pilot Project sand thicknesses and typical Frio sand permeabilities.

In the first and third simulations, the fault block is completely sealed, with a fault at y = 0 assumed to seal the SW boundary of the fault block (this is the case considered in earlier models). In the second and fourth simulations, the model extends for a long way in the -y direction, to represent an unsealed fault compartment.

Model Construction

In **Figure 10,** frames (a)-(c) show the three depositional settings making up the model, each of which includes three facies. Facies are arranged stochastically using the TproGS software. The upper thick sand is discretized into five layers of gridblocks, and the two underlying shaly layers are discretized into two grid layers each. Lateral gridblock spacing is finer around the injection and observation wells. Each layer is rotated 15^{o} about the x-axis, as shown in frames (d) and (e), to represent a dipping formation. Frame (d) depicts the complete model and frame (e) shows a cut-away view along the line joining the injection and observation wells. Table 1 gives the permeabilities and porosities of the various facies.

The top and bottom boundaries of the model are closed to represent continuous sealing shale layers. Three of the four lateral boundaries of the model (NE, NW, SE) are closed to simulate vertical faults. In the SW direction, the open version of the model actually extends much farther than shown (y = 9,000 m), to represent an incompletely sealed fault block. This is a geologically plausible change from previous pilot-site simulations, because no fault has been identified southwest of the site.

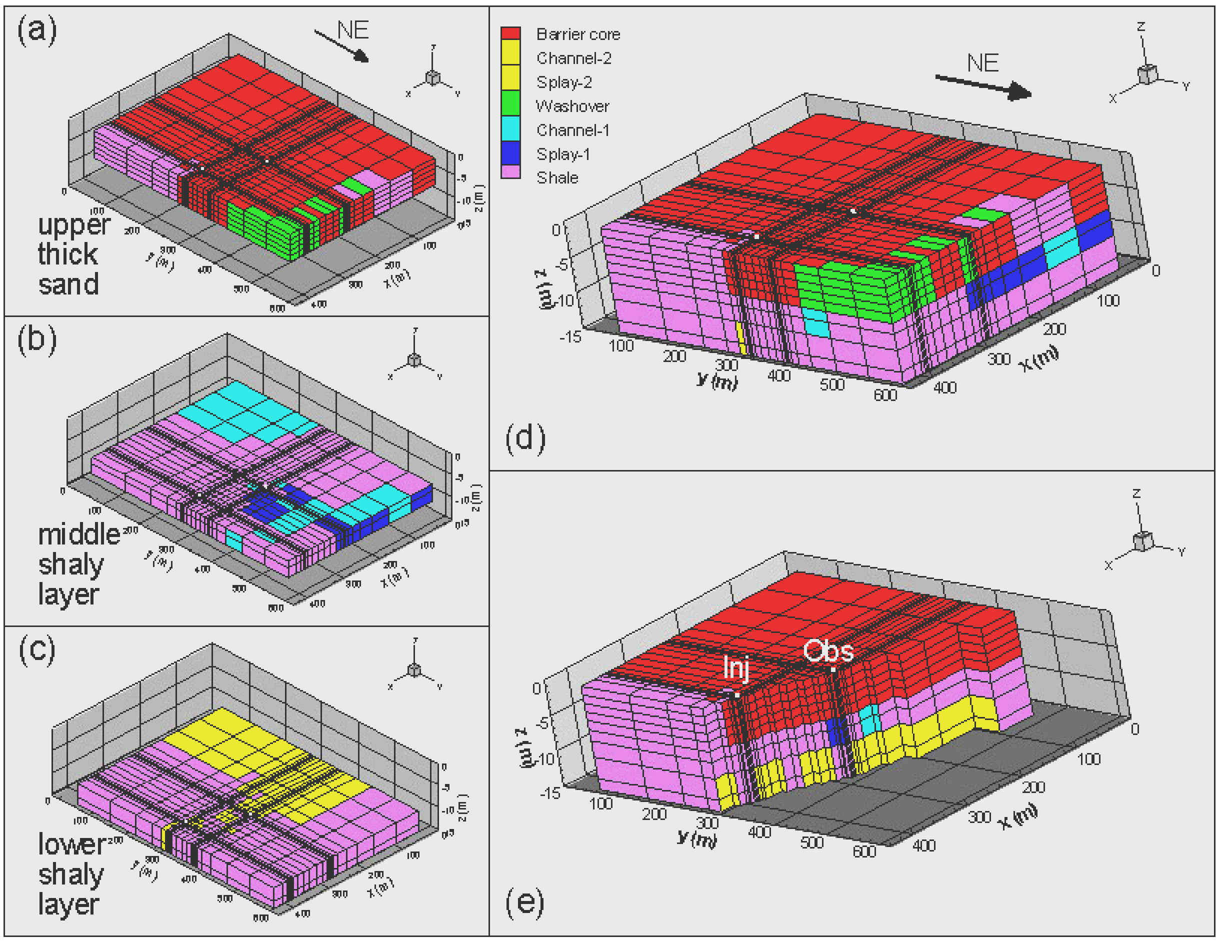

Figure 10. The TOUGH2 model of the “B sand” at the Frio Brine Pilot Project site. Frames (a)-(c) show the three depositional settings individually as flat layers, Frame (d) shows the complete model including the 15^{o} degree dip, and Frame (e) shows a cut-away view along the line between the proposed injection and observation wells.

Table 1. The permeabilities and porosities of the various facies

Facies	Porosity (%)	Horizontal Permeability (md)	Vertical Permeability (md)
Barrier core	32	700	700
Channel-2	30	400	100
Splay-2	30	150	30
Washover	29	200	50
Channel-1	30	100	70
Splay-1	28	30	20
Shale	10	0.001	0.0001

Results

Case 1. Injection at 50 tonnes per day for 100 days, closed model. The gas (actually supercritical CO_2) saturation distributions for the top layer of the model are shown in **Figure 11** for different times. Note that there is some shale in the lower right (southern) corner of the model, which the CO_2 plume avoids. Otherwise, the plume is controlled by buoyancy. The plume is small compared to the compartment size, so the lateral boundaries are not strongly felt.

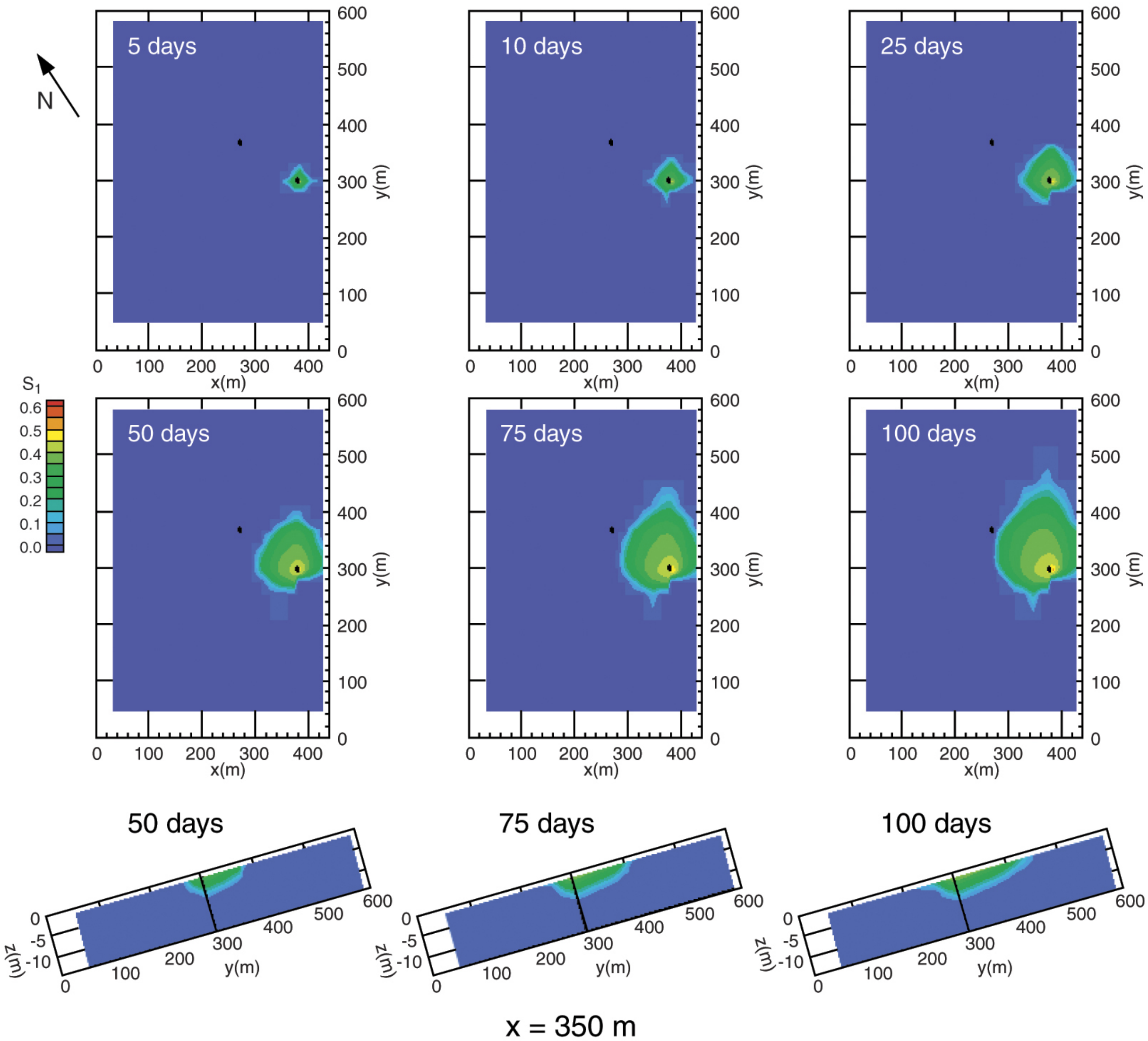

Figure 11. Case 1: Supercritical CO_2 distributions during the 100-day injection period

Case 2. Injection at 50 tonnes per day for 100 days, extended model. Carbon dioxide saturation distributions for the top layer of the model are shown in **Figure 12.** Pressure does not increase as much in the extended model as in the closed model, so CO_2 density is a little lower, resulting in a slightly bigger plume. Otherwise, the effect of the SW boundary being opened or closed is minor. Note in the cross-sectional plots that buoyancy flow is significant, with the plume extending much farther updip than downdip.

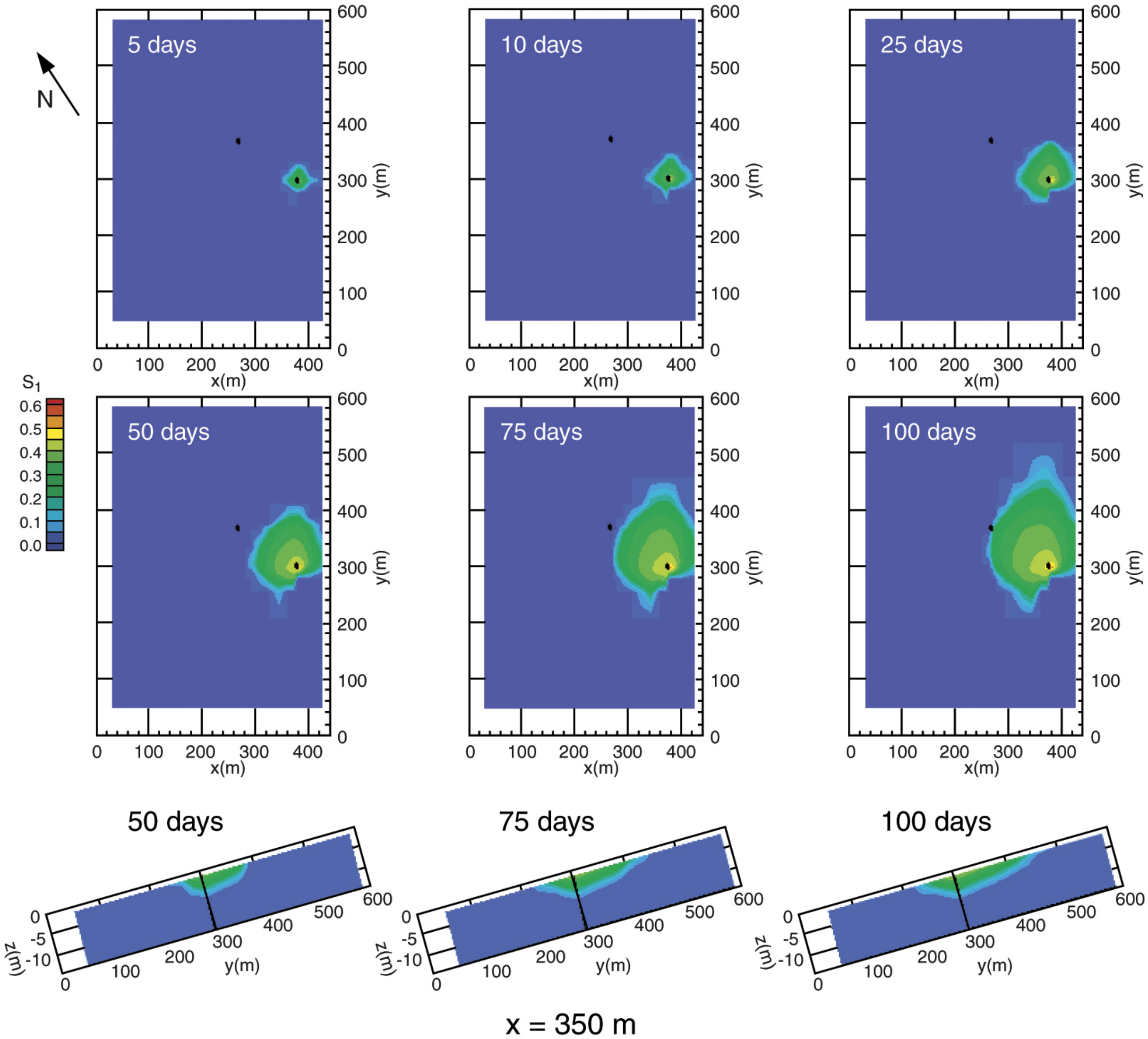

Figure 12. Case 2: Supercritical CO_2 distributions during the 100-day injection period

Case 3. This case considers the injection of 150 tonnes of CO_2 per day into a closed model during a 100-day period. Since the pressure increase is unacceptably large, the saturation distributions are not shown.

Case 4. Injection at 150 tonnes per day, extended model. Unlike the lower injection rate, here the lateral closed boundaries updip of the injection well counteract buoyancy flow to some extent, creating a CO_2 plume that is more symmetrically spread around the injection well. **Figure 13** shows CO_2 distribution for the first 100 days of the injection period, and **Figures 14 and 15** depict the distributions later in the year.

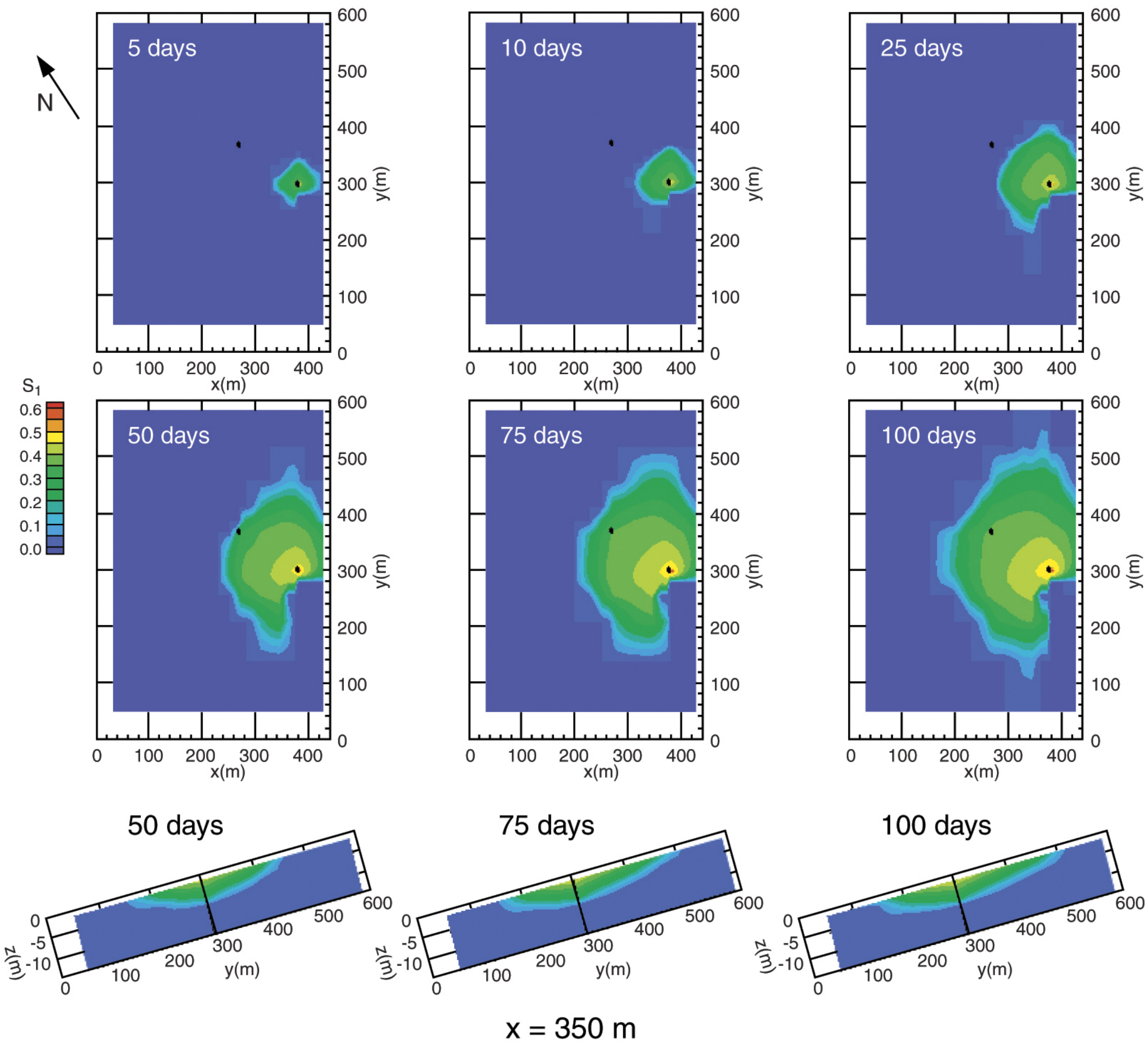

Figure 13. Case 4: Supercritical CO_2 distributions during the first 100 days of the injection

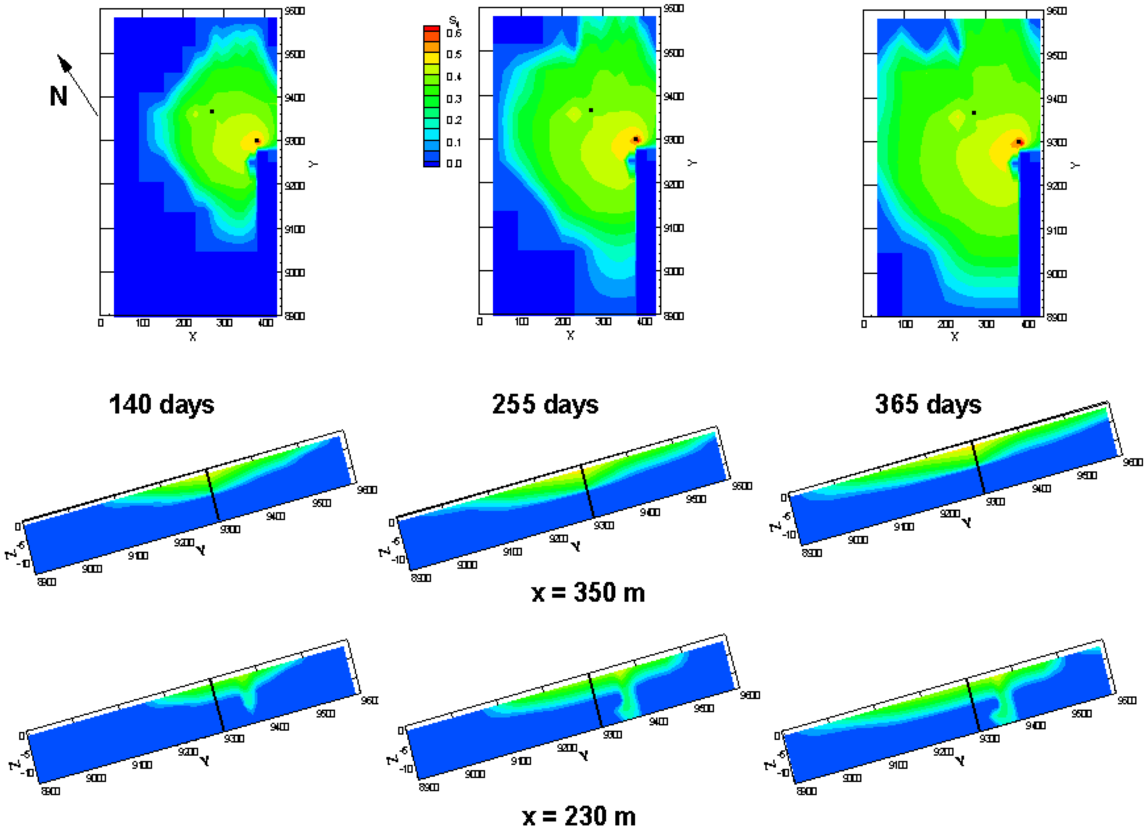

Figure 14. Case 4: Supercritical CO_2 distributions during the latter part of a one-year injection period

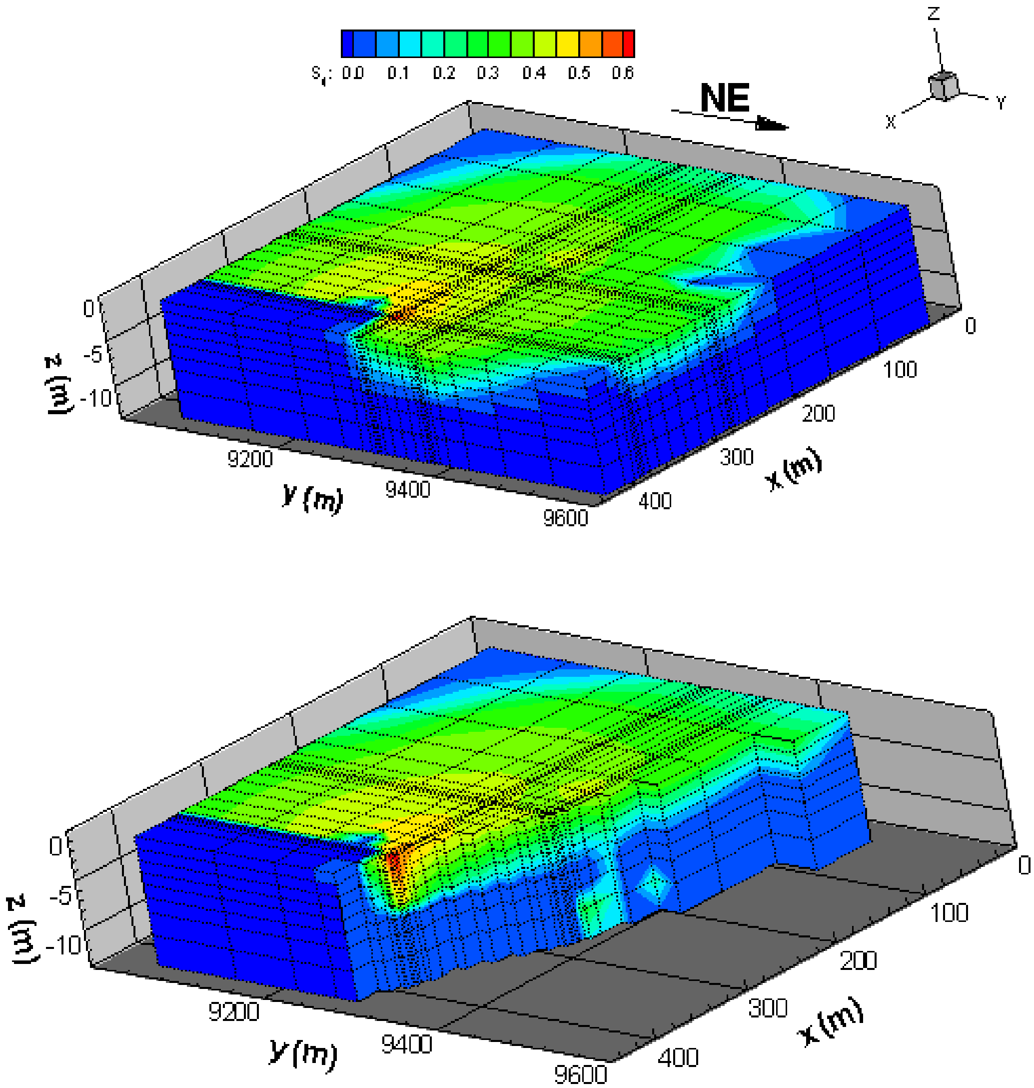

Figure 15. Case 4: Another view of the CO_2 distribution after one year of injection

Figure 16 shows the pressure response at the injection well for all cases. Initial pressure is about 150 bars. The pressure increase for the 150 tonnes per day, closed model (Case 3), is unacceptably large.

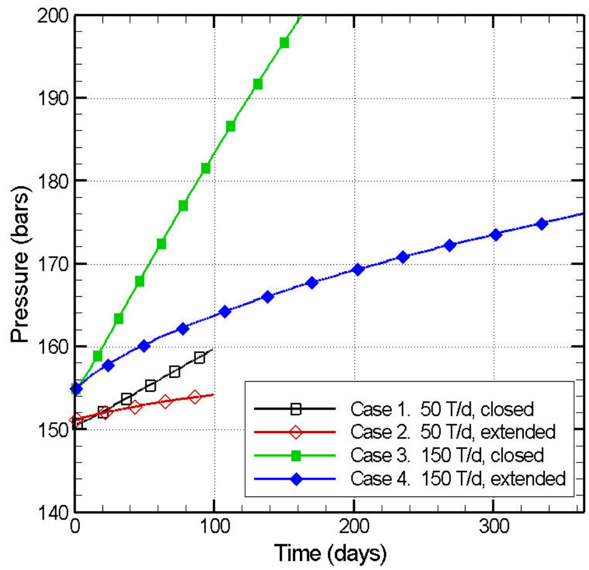

Figure 16. Pressure response near the injection well for the various cases considered

The above simulation cases have illustrated that CO_2 plumes that are small relative to the compartment into which they are injected behave quite differently than larger plumes. For small plumes, lateral boundary conditions play a far less important role than for large plumes. More generally, the finding that different physical processes control different-sized CO_2 plumes has important ramifications for modeling the pilot test. Specifically, extrapolating model results for one set of experimental conditions to a modified experiment design can be risky.

As part of this task, the concept of sequestration effectiveness was assessed. Sequestration effectiveness describes the volume of CO_2 that will be sequestered in a given time period and given subsurface volume. The assessment looked at sequestration capacity over time, identifying residence time in the injection horizon, characterizing flux upward to near surface environments and to the atmosphere, and considered the long-term fate and environmental risks of storing CO_2 in a geologically complex environment. A given volume of CO_2 distributed over a large rock volume may decrease rates of flux out of the injection horizon by shortening the continuous column of buoyant gas acting on a capillary seal and inhibiting seal failure. However, where structural heterogeneity predominates over stratigraphic heterogeneity, large columns of CO_2 may accumulate below a sealing layer, increasing the risk of seal failure and leakage (this is based upon hydrocarbon reservoir experiences). Issues defined as needing quantification include (1) role of trapping, (2) performance of faults, and (3) improved calculation of residual CO_2 saturations.

A review of the concepts of sequestration capacity and effectiveness was prepared for a special publication of the Geological Society on geologic sequestration.

Work Next Quarter

Further simulations will replicate more closely the currently envisioned pilot-site test conditions: (1) a shorter duration injection period (30 or 60 days rather than 100 days) at a correspondingly higher injection rate, and (2) a total of 7,500 tonnes of CO_2 injected rather than 5,000 tonnes. The value of drilling a new monitoring well that is closer to the injection well will also be examined.

The geological model will be improved as new data become available. Recent evidence suggests that the dip of the sand between the current injection and monitoring wells may be up to 30°. Additionally, the sealing nature of the subvertical faults forming the compartment's lateral boundaries has been questioned. Studies using steeper dips and faults that are open to fluid flow will be conducted.

Tools to assess the intermediate and long-term transport of CO_2 from the injection site to subsurface environments will be developed. The issues to be addressed include improving the assessment of residual saturation, which may control plume length, the effectiveness of seals, and the description of CO_2 flux at faults, using hydrocarbons as an analog. Literature will be reviewed and concepts that can be used to create quantitative models will be developed.

Resources to explain CO_2 geological sequestration to students and the general public will be look for and/or created.

Task E: Frio Brine Pilot Project

Goals

To perform numerical simulations and conduct experiments at the Frio Brine Pilot site, near Houston, Texas, that:

1. Demonstrate that CO_2 can be injected into a saline formation without adverse health, safety, or environmental effects.
2. Determine the subsurface location and distribution of the CO_2 cloud.
3. Demonstrate understanding of conceptual models.
4. Develop experience necessary for success of large-scale CO_2 injection experiments.

Note: This task does not include work being done by the Texas Bureau of Economic Geology under the project "Optimal Geological Environments for Carbon Dioxide Disposal in Brine Formations (Saline Aquifers) in the United States," funded under a separate contract.

Accomplishments This Quarter

- The first planning meeting for this project was held in mid-April.
- Main project activities were defined during the planning meeting.

Progress This Quarter

On April 12, a planning meeting was held in Berkeley to further define the role of the GEOSEQ team in conducting Frio Brine Pilot Project tests. Four main goals were established for the project. These are, in order of priority:

1. Demonstrate that CO_2 can be injected into a saline formation without adverse health, safety, or environmental effects.

Specific issues related to this goal are:

- Blowouts at wells
- CO2 in water wells
- Deleterious effects on environment (humans, flora, or fauna)
- CO2 leakage into houses or man-made structures
- Induced earthquakes
- Adverse effects on oil and gas operations
- Regulatory requirements.

These issues will be addressed proactively during the two-year experiment. In addition, the project will address the long-term fate of CO_2 in the subsurface to demonstrate that there are no anticipated adverse long-term effects from the experiment.

2. Determine the subsurface location and distribution of the CO_2 plume.
3. Demonstrate understanding of conceptual models.
4. Develop the experience necessary for success of large-scale CO_2 injection experiments.

Teams were created to evaluate the feasibility and effectiveness of a pallet of methods that are proposed to accomplish these goals, and a July 8-9, 2002, follow-up meeting was set up to evaluate the results of these assessments.

Work Next Quarter

A second meeting to review the latest results of simulations and modeling related to the Frio Brine Pilot Project and to design field and laboratory activities is scheduled to be held in Austin on July 8-9, 2002. The meeting will focus on coordination between the GEO-SEQ team and others working on the field test program to get the pilot into the field as soon as possible. The GEO-SEQ contributions will be critical in designing an effective experiment and obtaining necessary permits.